18th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
9-12 October 2017, Bologna, Italy

The air quality in urban canyons with tight and wide buildings

Michela Garau[1], M.Grazia Badas[1], Simone Ferrari[1], Alessandro Seoni[1], Giorgio Querzoli[1]

[1]Department of Civil, Environmental Engineering and Architecture, (DICAAR)
University of Cagliari, Italy

Abstract: Natural ventilation dynamics in urban street canyons plays a central role in planning of healthy urban areas. The study of idealized and simplified geometries is fundamental to unveil the mechanism driving air ventilation and mixing, hence much attention was given in literature to simple building configurations. Several authors analysed two-dimensional canyons, focusing on the influence of the canyon aspect ratio (AR_C, i.e. the ratio of the canyon width, W, to the building height, H). The purpose of this work is to gain further insight into the influence of the building shape on street canyon flow, especially investigating the role played by the building aspect ratio (AR_B, i.e. the ratio of the building width, W_B, to the building height, H). We carried out a series of Large Eddy Simulations of the flow above arrays of parallelepipedal buildings with AR_C = 0.5 and AR_C = 1 and AR_B in the range from 0.5 to 2. Numerical simulations were validated with laboratory data obtained in a water channel. Velocity measurements were performed by a non-intrusive image analysis technique (Feature Tracking Velocimetry). The flow characteristics are discussed in terms of velocity statistics and air exchange between canyon and overhead flow. Results show the implication on the flow patterns and the canyon ventilation of the two parameters, and suggest that AR_B and AR_C can be optimized in order to guarantee the maximum outflow rate.

Key words: *Urban Canyon, Air ventilation, Building Aspect Ratio, Canyon Aspect Ratio.*

INTRODUCTION

Poor air quality is a serious problem especially in modern, large cities and it is responsible for chronic and acute damages on human health. Pollutant transport and dispersion are directly linked with natural ventilation, which depends on a large number of factors, such as buildings shape, green areas, topography, wind direction, etc. Many experimental and numerical studies dealt with urban flows over both schematic and complex building geometries, focusing on different spatial scales. For instance, some authors considered isolated buildings immersed in a boundary layer, in order to describe the main tridimensional flow structures (Castro and Robins, 1977; Martinuzzi and Tropea, 1993). Other studies (e.g Oke, 1988) focused on the different flow regimes occurring in idealized street canyons, depending on the canyon aspect ratio, AR_C (which is defined as the ratio of street width to building height, AR_C = W/H). Millward-Hopkins et al. (2011) tried to summarize the overall effect of geometry in a city, using tri-dimensional blocks with AR_C ranging from 0.5 to 5. Zaki et al. (2011) performed numerical simulations in which spatial distribution, density and height of the buildings were randomly varied.
As regards the building aspect ratio, AR_B (i.e. defined as the ratio of building width to height, AR_B = W_B/H), Hang and Li (2011) set up numerical simulations and wind tunnel experiments, by varying the height of buildings (H from 1.5W_B to 2.67W_B) and similarly other authors carried on measurements by means 3D arrangement of buildings with different AR_C and AR_B (Chan et al. 2003; Kanda, 2006). However, these analyses were performed using tri-dimensional arrangement of parallelepipedal blocks.
Focusing on 2D street canyons, most of the works reported in literature are aimed at evaluating the influence of the AR_C on flow and pollutant dispersion, mainly considering AR_C = 1, 2 (Bernardino et al., 2015; Brown et al., 2000; Cui et al., 2004; Neophytou et al., 2014) and, in some cases, extending the range up to 5, e.g. Li et al. (2008). On the other hand, less attention has been devoted to study the effect of the building aspect ratio, AR_B. Therefore, different configuration of 2D building arrays, immersed in a neutrally stratified boundary layer, were here simulated with the aim to investigate the influence of the shape parameter of both the buildings and the canyons, AR_B and AR_C.

METHODS

We focused on the flow in urban canyons formed by a virtually infinite array of identical buildings with flat roof and a constant flow perpendicular to the canyon axis. We performed 8 different configurations considering two AR_C values (0.5 and 1) and AR_B ranging from 0.5 to 2, by the Large Eddy Simulation technique and 2 arrangement by means of flume water channel simulations (AR_C = 0.5, 1 and AR_B = 1), in order to validate the numerical ones.

Numerical Simulations

Large Eddy Simulation technique with the Smagorinsky subgrid scale model (Smagorinsky, 1963) was used in order to perform numerical simulations, making use of the open source library OpenFOAM 2.3.1, which solves the approximate form of the governing equations by means of the finite volume method (FVM). Second-order-accurate schemes were used for the time and space derivatives. The large time-step transient solver for incompressible flow, was employed for the pressure-velocity coupling scheme, using the PIMPLE algorithm (merged PISO-SIMPLE). All LES simulations were initialised with the solution of a previously run Reynolds-Averaged Navier-Stokes (RANS) simulation.

The 8 different building configurations were performed by imposing periodic boundary conditions both in the streamwise direction, in order to simulate an indefinite succession of buildings, and in the spanwise direction, in order to mimic a series of idealized 2D street canyons. The spatial domain, which consists of 3 canyons and 4 buildings (the side buildings are halved), is 9H in the vertical direction (z axis) and 9H in the spanwise one (y axis). Domain size in the streamwise direction (x axis), measured in building height units, ranges from 3H to 9H, depending on the building width. Structured mesh with grid stretching both in streamwise and vertical direction, is employed in order to discretize the domain: a higher resolution is used near the buildings walls and the street (0.016H), whist in the canyon centre the cell size is doubled. As a consequence, the total number of cell of ranges from the minimum of $2.7*10^6$ (in the case of AR_B = 0.5 and AR_C = 0.5) to a maximum of $9.26*10^6$ (in the case of AR_B = 2 and AR_C= 1). A mean streamwise velocity was imposed in order to obtain a Reynolds number higher than 3400 ($Re = U*H/\nu = 7000$), at the building height. The dimensional time-step increment was set in order to assure that the Courant number was always smaller than 0.6 at all grid points. The results were averaged over a minimum of 1350 time steps, as well as in the spanwise direction verifying that the simulation time was sufficient to obtain statistically-steady and representative results.

Experimental Simulations

Experimental simulations were carried out in a closed-loop water-channel, 6.5 m long and with a section 0.4 m wide and 0.5 m height: a series of 20 identical blocks, painted black in order to avoid laser light reflections, were set 4m downstream from the head of the channel, where a turbulent boundary layer is fully developed. In order to achieve a completely developed turbulence and a logarithmic velocity profile, a double grid with a honeycomb structure was placed at the head of channel and a 3 m long series of panels with loose gravel (d_e=0.01 m) was fixed on the channel bottom. A weir at the end of the channel imposes the maximum water level 0.4 m length. The incoming velocity profile is logarithmic up to 0.14 m (corresponding to 7H), with a maximum velocity of 0.36 m/s, and was positively compared and validated with the data of Farell and Iyengar (1999). At the building height (H), a Reynolds number $Re_H=U_HH/\nu=5000$ was obtained, a condition which satisfied $Re_H>3400$ as requested by Hoydish et al. (1974). The vertical streamwise mid-plane of the channel was illuminated by a diode laser emitting green light (532 nm in wavelength), through an optical system consisting of a cylindrical lens and a mirror. A high-speed camera (2240*1760 pixels) was employed with a 310 Hz frequency, acquiring the images in 40 separate recording sessions (1200 images each) in order to increase the statistical independence of the velocity data set. Thanks to neutrally buoyant particles homogeneously dispersed in the flow, the application of the non-intrusive image analysis technique, FTV (Feature Tracking Velocimetry), described in Besalduch et al. (2013) and in Ferrari et al. (2014), to couples of successive images allowed obtaining for each configuration, 48000 velocity fields on the last but two canyon downstream.

DISCUSSION

In order to validate our numerical and experimental set-up, we first compared obtained results to other available data (Brown et al., 2000, Cui et al., 2004, Cheng and Liu, 2011) for the reference case mainly investigated in literature (AR_B = AR_C =1). We compared 5 vertical profiles (x/H = -0.4, -0.25, 0, 0.25, 0.4) from the 1st to the 3rd order velocity statistics, obtaining a very good agreement, proving that the adopted modelling is sound. We here show only vertical profiles at the canyon central point, x/H = 0, for the streamwise velocity (Fig.1 A), made non-dimensional for the mean velocity between z/H=1 and z/H=1.5) and the streamwise velocity skewness factor (Fig.1B).

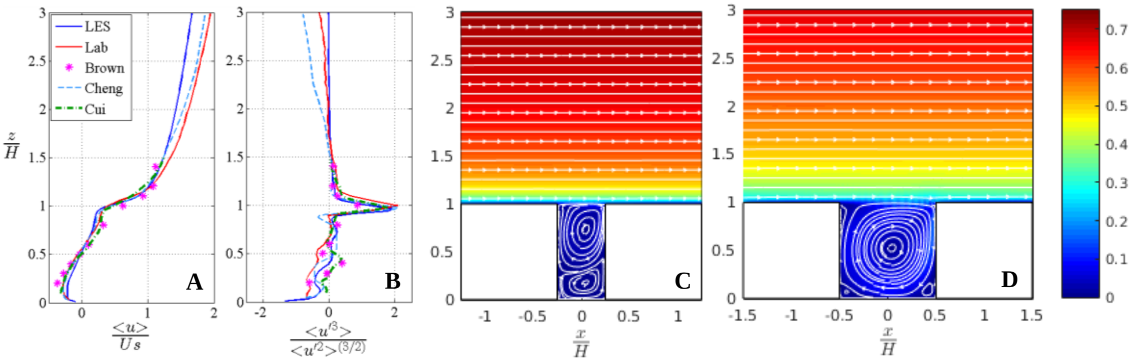

Figure 1. On the left part of the panel: vertical profiles of non-dimensional streamwise velocity (A) and skewness factor (B). Solid blue line: numerical simulations, solid red line: experimental results, dashed green line: numerical results of Cui et al. (2004), dashed cyan line: numerical simulations of Cheng and Liu (2011), pink asterisk: experimental results of Brown et al. (2000). On the right part of the panel: the comparison between two cases with the same building aspect ratio (AR_B = 1) and different canyon aspect ratio, AR_C = 0.5 (C) and AR_C = 1 (D).

The other experimentally simulated case, AR_C = 0.5 and AR_B = 1, provided comparable results to the numerical corresponding one, proving the reliability of the LES data. Qualitative results for the mean velocity magnitude, obtained from numerical simulations (AR_C = 0.5, 1 and AR_B = 1 respectively in Fig. 1 C and D), show a completely different behaviour inside the canyon depending on the AR_C parameter: instead of a single main vortex (Fig. 1 D) in the narrow canyon there are two counter-rotating vortexes, as a consequence of the increase of the height respect to the canyon width. This phenomenon has been already studied by different authors (e.g. Kovar et al., 2002) and might represent a real negative aspect for the air exchange between the canyon and the overhead air, with a possible different effect depending on AR_B. With the aim to synthetically compare the different configurations, all the statistics have been spatially averaged from the middle point of the upwind building to the middle point of the downwind one.

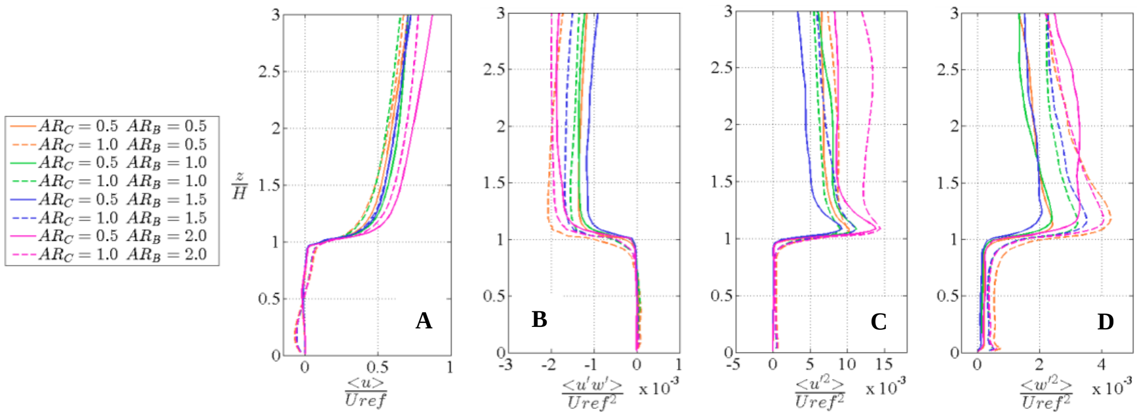

Figure 2. Vertical profile of non-dimensional horizontally averaged streamwise velocity (A), vertical flux of streamwise momentum (B), streamwise velocity variance (C) vertical velocity variance (D). Solid lines indicate the configurations with AR_C = 0.5 and dashed lines indicates the configurations with AR_C = 1. Different colours indicate different values of AR_B (orange: AR_B = 0.5, green: AR_B = 1, blue: AR_B = 1.5, pink: AR_B = 2).

The resulting horizontally averaged profiles, made non-dimensional by the free-stream velocity at z/H=9, are reported in Fig.2. Inside the canyon the differences due to AR_B are almost negligible, whilst two different trends can be identified for AR_C = 0.5 and AR_C = 1. This is more evident in the mean velocity profile (Fig. 2 A), due to the already mentioned different flow pattern. The influence of the AR_B parameter is more apparent outside the canyon cavity, where the profiles do not collapse on a single curve. For z/H >1 the horizontally-averaged turbulent momentum flux (Fig.2 B) is negative and for all the analysed configurations, the curves present a maximum just above the roof, around the height z/H = 1.15; the configuration that showed the highest value is AR_C = 1, AR_B = 0.5, where the ratio of the building horizontal area to the canyon area is minimum. This is mainly caused by the vertical component of the flux, as confirmed by the variance profiles. Turbulent momentum flux are shifted towards more negative values when considering cases with increasing AR_C and the same AR_B value. Both the variance velocity components show a significant increase of the turbulence just above the roof, as a consequence of the canopy presence: variances present a systematic increase when the building width increases, only for AR_C = 1 and AR_B greater than 0.5.

In order to better understand ventilation condition and the capability of the air exchange into the canyon, we estimated φ_e, which is the outflow rate across a generic interfacial surface. The bulk air exchange between the canyon and the external boundary flow is mainly linked to the interfacial surface at the roof level, however it is useful to compute this index at different canyon heights in order to provide a comprehensive picture of the phenomenon and better investigate mixing at pedestrian level. We computed both the mean outflow rate due to the instantaneous velocity field, equation (1), and the outflow due to the mean velocity field, equation (2):

$$\varphi_e(z) = \frac{1}{2}\overline{\int_W |w(t)|dx} \qquad (1)$$

$$\varphi_{em}(z) = \frac{1}{2}\int_W |\overline{w}|dx \qquad (2)$$

Results in Fig. 3, show a completely different trend between two series of data: for AR_C = 0.5 (Fig. 3 A), φ_{em} and is always lower than φ_e, especially at the lowest half portion of the canyon and, quantitatively, both φ_e and φ_{em} are about halved with respect to those of the larger canyon (Fig. 3 B). In the canyon with AR_C = 0.5 (Fig. 3A), the curves present the minimum value for both parameters for low z/H levels, with consistent lower values of φ_{em} with respect to φ_e, while the maximum for both φ_{em} and φ_e is at the same height, around z/H = 0.75. This situation confirm a generally poor air ventilation in narrow canyons, which is however halved by the turbulent fluxes, especially at the lower pedestrian level. Nonetheless this scenario can highly influenced by the building aspect ratio. Instead, for AR_C = 1 (Fig. 3B), φ_{em} and φ_e trend are very close and every configuration maintains the same trend with a maximum near the height z/H = 0.5. However, a distinct behaviour is apparent for the configuration AR_C = 1, AR_B = 0.5, whose curves follow a similar trend, but are shifted towards higher values, both for φ_{em} and φ_e. This is more visible around the maximum point and around the roof level, where the increment is around 20% with respect to the other analysed cases.

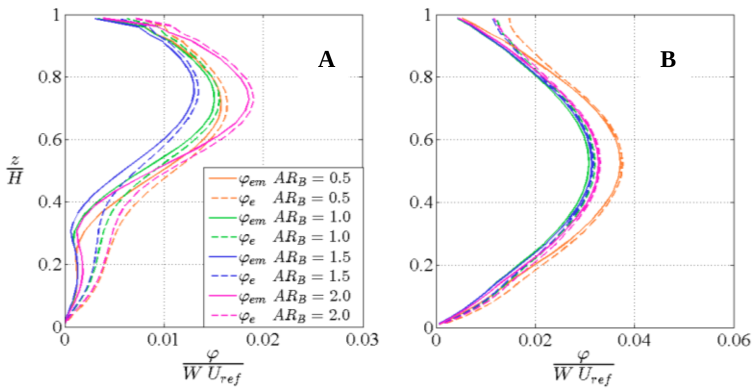

Figure 3. Non-dimensional vertical profiles of outflow rates calculated for AR_C = 0.5 (A) and AR_C = 1 (B), for different heights inside the canyon. Solid lines indicate φ_e and dashed lines φ_{em}, made non-dimensional by the free-stream velocity U_{ref} and the canyon width W. Different colours correspond to different values of AR_B (orange: AR_B = 0.5, green: AR_B = 1, blue: AR_B = 1.5, pink: AR_B = 2).

CONCLUSIONS

We employed both numerical LES simulations and hydraulic water flume experiments in order to investigate flow and ventilation in 2D urban canyons array of identical buildings with flat roof. Eight configurations were analysed considering two aspect ratios for the canyon (AR_C = 0.5 and 1) and 4 for the buildings (AR_B = 0.5, 1, 1.5, 2). Results showed a different behaviour, not only in the flow pattern but also for the ventilation mechanism. To sum up, the configuration with AR_C = 1, AR_B = 0.5, achieved the maximum turbulence level and it guaranteed the maximum exchange level for all the canyon depth. This result suggests that there is an optimal ratio of the building to the canyon horizontal area which maximizes the air exchange.

REFERENCES

Bernardino, A.D., P. Monti, G. Leuzzi and G. Querzoli, 2015: Water-Channel Study of Flow and Turbulence Past a Two-Dimensional Array of Obstacles. Bound.-Layer Meteorol. 155, 73–85.

Besalduch, L.A., M.G., Badas, S., Ferrari, G., Querzoli, 2013: Experimental Studies for the characterization of the mixing processes in negative buoyant jets. EPJ Web Conf. 45:01012

Brown, M.J., R.E. Lawson , D.S. Decroix and R.L Lee., 2000: Mean Flow and Turbulence Measurements Around a 2-D Array of Buildings in a Wind Tunnel

Castro, I.P. and A.G. Robins, 1977: The flow around a surface-mounted cube in uniform and turbulent streams. J. Fluid Mech. 79, 307–335.

Chan, A.T., W.T.W. Au and E.S.P. So, 2003: Strategic guidelines for street canyon geometry to achieve sustainable street air quality-part II: Multiple canopies and canyons. Atmos.Environ.37,2761-2772

Cheng, W.C. and C.-H. Liu, 2011: Large-Eddy Simulation of Flow and Pollutant Transports in and Above Two-Dimensional Idealized Street Canyons. Bound.-Layer Meteorol. 139, 411–437.

Cui, Z., X. Cai and C.J. Baker, 2004: Large-eddy simulation of turbulent flow in a street canyon. Q. J. R. Meteorol. Soc. 130, 1373–1394.

Fackrell, J.E., 1984: An examination of simple models for building influenced dispersion. Atmospheric Environ. 1967 18, 89–98.

Ferrari, S., M.G. Badas, L.A. Besalduch, G. Querzoli, 2014: A Feature Tracking Velocimetry technique applied to inclined negatively buoyant

Hang, J. and Y. Li, 2011: Age of air and air exchange efficiency in high-rise urban areas and its link to pollutant dilution. Atmos. Environ. 45, 5572–5585.

Kanda, M., 2006: Large-Eddy Simulations on the Effects of Surface Geometry of Building Arrays on Turbulent Organized Structures. Bound.-Layer Meteorol. 118, 151–168.

Kovar, A. P. Louka, J.F. Sini, E. Savory, M. Czech, A. Abdelqari and P.G. Mestayer, N. Toy, 2002: Influence of geometry on the mean flow within urban street canyons-a comparison of wind tunnel experiments and numerical simulations. Int. J.Water Air Soil Pollut. Focus, 2. pp 365-380

Li, X.-X., C.-H. Liu and D.Y.C. Leung, 2008: Large-Eddy Simulation of Flow and Pollutant Dispersion in High-Aspect-Ratio Urban Street Canyons with Wall Model. Bound.-Layer Meteorol. 129, 249–268.

Martinuzzi, R. and C. Tropea, 1993: The Flow Around Surface-Mounted, Prismatic Obstacles Placed in a Fully Developed Channel Flow (Data Bank Contribution). J. Fluids Eng. 115, 85–92.

Millward-Hopkins, J.T., A.S. Tomlin, L. Ma, D. Ingham and M. Pourkashanian, 2011: Estimating Aerodynamic Parameters of Urban-Like Surfaces with Heterogeneous Building Heights. Bound.-Layer Meteorol. 141, 443–465.

Neophytou, M.K.-A., C.N. Markides and P.A. Fokaides, 2014: An experimental study of the flow through and over two dimensional rectangular roughness elements: Deductions for urban boundary layer parameterizations and exchange processes. Phys. Fluids 26, 086603.

Oke, T.R., 1988: Street design and urban canopy layer climate. Energy Build. 11, 103–113.

Smagorinsky, J., 1963: General circulation experiments with the primitive equations. Mon. Weather Rev. 91, 99–164.

Zaki, S.A., A. Hagishima, J. Tanimoto and N. Ikegaya, 2011: Aerodynamic Parameters of Urban Building Arrays with Random Geometries. Bound.-Layer Meteorol. 138, 99–120.